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CYLINDRICAL LINEAR INDUCTION MOTOR WITH INTERMITTENT PHASE SWITCHING USED IN THE BOREHOLE PLUNGER PUMP DRIVE WITH MECHANICAL ENERGY STORAGE ELEMENTS

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ABSTRACT

This paper discusses a mathematical model and an experimental plant developed and studied for a borehole plunger pump driven by the cylindrical linear induction motor (CLIM) and equipped with elastic elements of mechanical energy storage, where a single phase switching is performed at a three phase power supply. A design was put forward for a borehole plunger pump equipped with the cylindrical linear induction motor and mechanical energy storage elastic elements. The design ensures energy efficient operation of the pump and enables its performance to be controlled. An open phase operation mode at the reverse stroke of the plunger reduces inrush currents when the linear motor is reversed.

KEYWORDS: Borehole Plunger Pump, Cylindrical Linear Induction Motor, Mechanical Energy Storage Elastic Elements, Open-Phase Operation, Control System, Mathematical Model & Experimental Plant

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1. INTRODUCTION

Borehole centrifugal pumps are most commonly used for water lifting, however, they suffer from low efficiency (10–25%), a complicated start-up, which in turn may often lead to outages and water lifting height limits.

Plunger pumps do not have the above mentioned drawbacks. However, an intermediate drive between the plunger and the rotation motor impedes the use of borehole plunger pumps in water supply. This imposes limits on performance control, increases specific amount of metal per structure and cost of the plant.

Electromagnets combined with elastic elements may be used to ensure oscillatory motion of the borehole plunger pump operating parts. Their main disadvantage is the difficulty in producing oscillations of 0.5–0.7 m amplitude and 0.1–0.5 Hz frequency (Aipov, 1994; Aipov & Valishin, 2017; Kuzo, 2013; Trofimenko & Naida, 2017; Zaman, 2018).

The use of the cylindrical linear induction motor as a driving motor may increase the efficiency, lower specific amount of metal per structure and cost of the pump. When it comes to the choice of an electric motor special attention should be paid to the energy characteristics of the electric motor which depends directly on the performed tasks. Aspects involved in the design and modelling of cylindrical linear induction motors should be considered in accordance with the operating mechanism requirements and its movement characteristics (Aipov, 1994; Aipov & Valishin, 2017; Linenko, 2015; Zhang & Lang, 2016).

So far, plunger pumps driven by linear induction motors have been mainly applied in oil industry (Wang, 2012; Guoxing, 2017; Qian, 2018). Reciprocating motion used in the pumps implies the rotor (the secondary) of the submersible linear motor is connected with the borehole pump plunger, so the plunger pump is directly actuated by the motor (Guoxing, 2017; Shanks, 2018). The existing designs of a water hydraulic piston type plunger pump driven by a linear motor are based on the distribution of valve and piston operation (Etter, 2018; Zhang, 2014).

Current developments of direct drive borehole plunger pumps are based on linear synchronous and asynchronous motors controlled by position sensors. The use of linear synchronous electric motor in the borehole plunger pump (Aipov et al., 2018; Yarullin, 2018) implies reversing. Electrically initiated reversing of the motor (Zhang, 2012) requires a counter-switching mode. In this mode, the motor consumes energy from the electric network (Zhang, 2012) which is twice as high as absorbed kinetic energy of the drive. Damping elements (spacers) are used to eliminate impacts of the plunger against the pump chamber. Energy-consuming counter-switching mode and impacts of the plunger against the pump chamber are eliminated in the proposed design through operation of the cylindrical linear induction motor (CLIM) combined with mechanical energy storage elastic elements (MESEE). In terms of energy related aspects, this approach is the most efficient. Energy storage elastic elements incorporated in the cylindrical linear induction motors ensure energy-efficient electric drive of oscillatory motion where the operating part is accelerated in one direction by electromagnetic field of the CLIM at a three phase supply and in the reverse direction by the stored energy in MESEE and CLIM operation at a two phase supply.

No energy consumption experienced in absorption of kinetic energy and its use in acceleration may reduce the energy from the electric grid. Potential energy storage element is an elastic element which together with kinetic energy accumulator, the mass (secondary element), forms an oscillating pair. Complete conversion of kinetic energy into potential energy and vice versa takes place at a frequency of the drive oscillation (Aipov, 1994; Aipov & Valishin, 2017; Linenko, 2015).

Various elastic elements may serve as an effective energy storage elements (Biderman, 1980). Cylindrical screw type springs are the most efficient (Biderman, 1980; Geng, 2015) as they ensure stable adjustment, have relatively small dimensions and masses, and are easy to assemble and use.

The authors introduce a gearless electric drive for the borehole plunger pump designed on the basis of a cylindrical linear induction motor with elastic elements of mechanical energy storage where the plunger performs complex and wide-range adjustable oscillatory motion (at an amplitude of up to 0.7 m and frequency of up to 0.5 Hz). The development opens up a new area for improvements in piston and plunger pumps.

The drive control system which combines energy-efficient operation of the pump and lower inrush currents of the electric drive is particularly significant for the design operation.

The aim of the study is to reduce energy costs in operation of the borehole plunger pump used for lifting water from a great depth borehole.

The following tasks must be solved to achieve the goal:

- Choosing an efficient design of a drive on a CLIM basis with elastic elements of mechanical energy storage for the borehole plunger pump.

- Using an open phase operation mode for the CLIM based drive with an intermittent single phase tripping at a three phase power supply.
- Developing a mathematical model of the borehole plunger pump drive on a CLIM basis which provides an intermittent one phase tripping at a three phase power supply.
- Examining consistent patterns of the CLIM operation for driving the borehole plunger pump to identify energy efficiency indices.
- Developing a control system for the plunger pump equipped with a cylindrical linear induction motor, the design and operation mode of the CLIM ensuring lower energy costs of the drive.

2.RESEARCH METHODS

To assess the efficiency of the borehole plunger pump on a CLIM basis, a mathematical model was developed that allows the time behaviour of the forces acting on the plunger to be obtained, the position and speed of the plunger to be determined and dependences observed in the plunger electric drive to be studied.

Differential equations of mechanical motion were used for mathematical description of the borehole plunger pump operation. The dependence of the motor thrust on its speed is determinant. The direction and origin for each stage of the plunger movement are counted from the extreme positions of the CLIM secondary (*I* – maximum amplitude). The countdown is selected individually for the forward (up) and reverse (down) movement of the plunger.

The design kinematic diagram of the bore hole plunger pump drive on a CLIM basis and forces acting on the plunger are shown in figure 1.

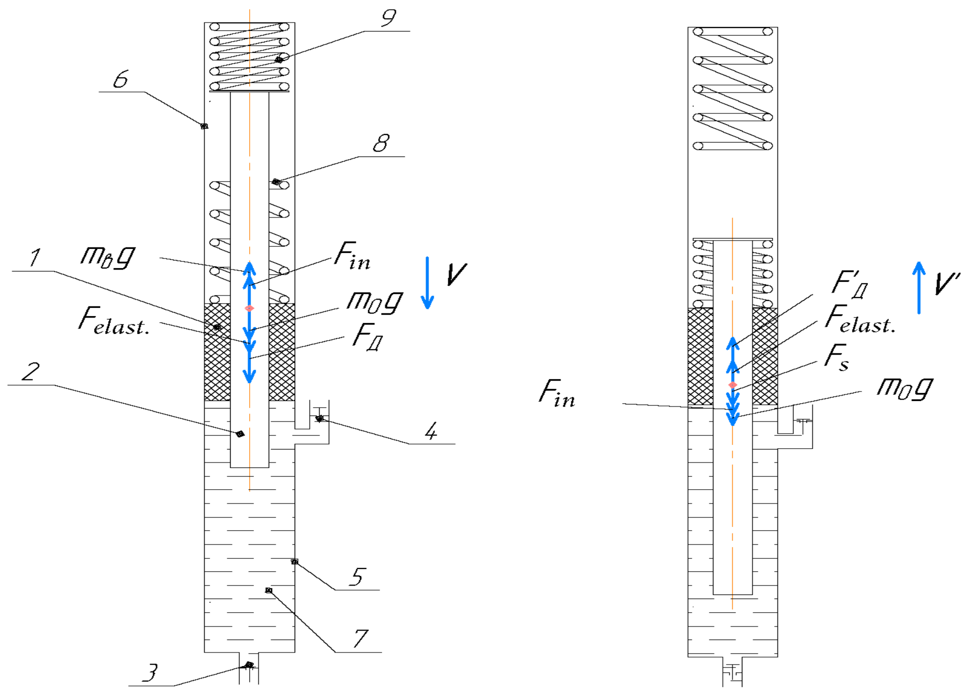

Figure 1: Kinematic Diagram of the Borehole Plunger Pump Driven by The CLIM: A- Forces Acting on the Plunger While Moving Down the Borehole; B- Forces Acting on The Plunger While Moving up the Borehole; 1 - CLIM; 2-Plunger; 3,4 - Valves; 5,6-Operating Chambers; 7- Water; 8,9 - Mechanical Energy Storage Elastic Elements; V- The Plunger Movement Speed.

Based on the design diagram here is a system of differential equations reflecting the plunger moving down (direct motion) and up (reverse motion):

$$\begin{cases} F_D dv(v) - m_в g - F_{inner}(v) + m_0 \cdot g + F_{elast} = (m_0 + m_в) \cdot \dfrac{dv}{dt}; \\ F_D' dv(v') - F_{inner}(v') - F_{inake}(v) - m_0 \cdot g + F_{elast} = m_0 \cdot \dfrac{dv'}{dt}, \end{cases} \quad (1)$$

where F_D *(v)*[$F_Д$ *(v)*] – dependence of the force exerted by the CLIM on the speed in a full phase mode, N; F_D*'(v')* [F_D*'(v')*] –the force of the CLIM in an open-phase (two-phase) mode, N; F_{intake} *(v)* [$F_{всас}$ *(v)*] – resistant force on the intake into the pump chamber, N; F_{pipe} *(v)* [$F_{труб}$ *(v)*] – resistant force exerted on the pipeline, N; F_{inner} *(v)* [$F_{внутр}$*(v)*] – inner resistant force of the CLIM and pump, N; F_{elast}[$F_{упруг}$] – elasticity force of the mechanical energy storage element, N; *v* – the plunger speed in a full phase mode, m/s; *v'* – the plunger speed in an open-phase phase mode, m/s; m_0 – mass of the pump moving parts taken without the mass of the water displaced, kg; m_b - mass of the water forced into the pipe, kg; *g* – free fall acceleration, m/c^2.

Mathematical modelling of electromagnetic processes in multipolar performance (the number of pole pairs p>4) of the CLIM is carried out on equivalent circuits using the well known Park–Gorev equation set. Allowances conventional for the procedure may be used in the modelling.

The orthogonal coordinate system *α, β, 0* fixed in relation to the inductor is common in considering assymetric CLIM operation modes. The *α* axis lies in the inductor axis, whereas the *β* axis is by *π*/2 angle beyond the inductor axis. The Park–Gorev equation set for the two-phase power supply of the CLIM inductor ("A" phase is switched off, for instance) is as follows:

$$\left. \begin{aligned} &\frac{d\psi_{\alpha1}}{dt} = U_{\alpha1} - \frac{\pi}{\tau} v_0 \alpha'_s \psi_{\alpha1} + \frac{\pi}{\tau} v_0 \alpha'_s K_r \psi_{\alpha2}; \\ &\frac{d\psi_{\beta1}}{dt} = U_{\beta1} - \frac{\pi}{\tau} v_0 \alpha'_s \psi_{\beta1} + \frac{\pi}{\tau} v_0 \alpha'_s K_r \psi_{\beta2}; \\ &\frac{d\psi_{\alpha1}}{dt} = -\frac{\pi}{\tau} v_0 \alpha'_r \psi_{\alpha2} + \frac{\pi}{\tau} v_0 \alpha'_r K_s \psi_{\alpha1} - \frac{\pi}{\tau} v \psi_{\beta2}; \\ &\frac{d\psi_{\beta1}}{dt} = -\frac{\pi}{\tau} v_0 \alpha'_r \psi_{\beta2} + \frac{\pi}{\tau} v_0 \alpha'_r K_s \psi_{\beta1} + \frac{\pi}{\tau} v \psi_{\alpha2}; \\ &U_{\alpha1} = -\frac{1}{3}(Ub + Uc);\ \ U_{\beta1} = \frac{1}{3}(Ub - Uc)); \\ &F`Д = \frac{3}{2} \frac{\pi^2 v_0 k_r}{\tau^2 \sigma x_s} (\psi_{\alpha2}\psi_{\beta1} - \psi_{\alpha1}\psi_{\beta2}). \end{aligned} \right\} \quad (2)$$

where $\psi_{\alpha1}, \psi_{\beta1}, \psi_{\alpha2}, \psi_{\beta2}$ – flux linkages along *α* and *β* axes of the inductor and the secondary, respectively; Ub, Uc – voltages of "B" and "C" phases; v_0 – synchronous speed of the CLIM electromagnetic field; τ – pole pitch of the CLIM winding; $\alpha'_s, \alpha'_r, K_s, K_r$ – coefficients used in the set equation are determined by the CLIM equivalent circuit parameters $\alpha'_s = \dfrac{R_1 X_r}{X_s X_r - X_m^2}$, $\alpha'_r = \dfrac{R'_2 X_s}{X_s X_r - X_m^2}$, $K_r = \dfrac{X_m}{X_r}$, $K_s = \dfrac{X_m}{X_s}$; σσσ – coefficient of magnetic flux leakage; x_s –inductive resistance of the inductor; $x_s = x_1 + x_m$, $x_r = x`_2 + x_m$ - inductive resistance of the secondary.

The inner resistance force of the CLIM secondary (the plunger) is determined by two resistance values of the rod seal:

$$F_{inner}(v) = 2 \cdot F_{rdfrct} \tag{3}$$

where $F_{rd\,frct}$ - friction force, it depends on the type of seal, N:

$$F_{rdfrct} = \mu \cdot \pi \cdot D_p \cdot b \tag{4}$$

where μ= 0.10…0.13 – friction coefficient of the cup against the rod operating surface, N/m^2;D_p – the plunger diameter, m; b – the seal width, m.

Cylindrical screw-type springs are used as elastic elements. The mathematical model uses Hooke's linear law to describe the force of the elastic elements:

$$F_{elast} = -k \cdot X \tag{5}$$

where F_{elast} – elasticity force, N; k, X – rigidity N/m and deformation of the elastic element, m, respectively.

Multiple integration involved in equations (1)–(5) explains non-linear nature of the discussed issue. Different ways of analytical representation of the equations at the stages of direct (at a three-phase power supply) and reverse (at a two-phase power supply) movement add more complexity. An object-visual simulation package Simulink (MATLAB) was used to solve the non-linear dynamic equation set. The mathematical model of the borehole plunger pump on a CLIM-basis is represented in the reference source.

The following values remain constant during the period of modelling t: the borehole height – H, m; the plunger mass – m_p, kg; the plunger diameter – D_p, mm; the pipeline diameter – D_t, mm, the intake pipe diameter – D_{tvsas}, mm; water density – r_o, kg/m^3; pole pitch – τ, synchronous speed – V_0, m/s and the CLIM equivalent circuit parameters.

The experimental plant used to study the characteristics of the borehole plunger pump on a CLIM basis has a module structure. This helps to examine the various types of CLIM, use plungers of various diameters and elastic elements of various specifications.

The control system enables necessary switching circuits to be used to obtain different operation modes for the CLIM, the motor operation at a three- and two-phase power supply in particular. The system also ensures a self-oscillating or forced oscillating mode and combines the time and plunger position-based control of the CLIM operation.

To obtain an open-phase operation mode for the borehole plunger pump using the CLIM in the drive an impulse control is employed based on the programmable logic controller to periodically trip one of the inductor phases off the electric grid.

Figure 2 shows the module diagram of the control system used in the borehole plunger pump on a CLIM basis.

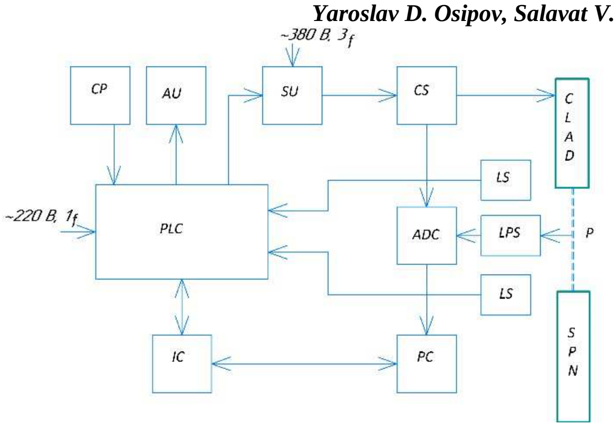

Figure 2: Module Diagram of the Control System used in the Borehole Plunger Pump on a CLIM Basis.

The following abbreviations are used in figure 2: ADC [АЦП]–analog-to-digital converter; SU [БК] – switching unit; AU [БС]–alarm unit; LS [ВК] – limit switch; LPS [ДЛП] – linear position sensor; CS [ДТ] – current sensor; PLC [ПЛК] – programmable logic converter; IC [ПИ] – interface converter; PC [ПК] – personal computer; CP [ПУ] – control panel; P [П] – plunger (the secondary).

The control system main units serve as:

- Programmable logic controller (PLC) ensures operation of the CLIM under standard conditions.
- Alarm Unit (AU) is located on the control panel and is used to indicate operating modes.
- The RS-485/USB interface converter (IC) connects the PLC to a personal computer (PC) and is needed to set the controller and schedule the control system operation.
- Switching Unit (SU) connects the CLIM to the power source on the specified scheme, that is, it disconnects one of the phases of the three-phase power supply system at certain time moments. So, the plunger reverses its movement at a two-phase power supply, that is, in an open phase operational mode.

Switching unit was designed based on a programmable relay to support analog signals for OVEN PR114 local systems and featuring 4 analog inputs and up to 8 discrete outputs which also enables solid-state relays (SSR) to be controlled. HDH-12044.ZD 3 series solid-state relays are designed to switch high load power supply circuits in one-or three-phase networks.

The SSR of the series feature, maximum current capacity up to 120 A; a wide switching voltage range of 40–440 volt; minimum switching disturbances in switch operation. Low switching disturbances are due to the fact that relay shifting occurs when the waves pass through the zero voltage level. This reduces the initial current in-rush as well as the level of electromagnetic disturbances and as a result increases switching load length.

Three SSRs are installed in each of the three phase to ensure the three phase load switching. This makes switching more reliable and improves the whole control system operation.

The potentiometer-type linear position sensor (LPS) "Gefran" LT-M-0500-s is used to determine the plunger position. Positioning of the plunger is needed to expand the operational mode of the borehole plunger pump.

The principle of the sensor operation is based on the change in the resistance value of the built-in AC resistor depending on the position of the rod in relation to the sensor housing, the position is thus determined by its linear movement. The voltage proportional to the displacement is taken from the displacement sensor output. The maximum measurable linear displacement for the sensor is 500 mm. About 10 V voltages in the sensor output corresponds to the maximum displacement. So, 0.2 V voltage corresponds to 10 mm displacement.

When the plant is started the plunger begins performing reciprocating motion with variable acceleration. The time dependence of the voltage proportional to the plunger position may be taken from the sensor output. The ADC adds the voltage changes to the computer memory. The obtained time dependences of the voltage are then converted to the corresponding plunger displacement, speed and acceleration dependences.

- Limit switches (LS) are triggered at a specified compression index of mechanical energy storage elastic elements. The maximum compression index of elastic elements of mechanical energy storage was determined by the results of mathematical modelling.
- The experimental plant designed to examine the features of the borehole plunger pump with the CLIM in the drive was equipped with the following measuring devices to take the current dependences in the CLIM inductor and determine the plunger position: current sensor, linear position sensor, analog-to-digital converter (ADC) connected to a personal computer.

The sensor signals were recorded by the ADC, a multichannel oscilloscope ACUTE DS-1000 series (model DS-1102). The device recorded the sensor signal in real time mode and displayed it on the computer screen, memorized and converted the signal for further processing, so that the data could be exported to external storage devices.

DS-1000 series devices are portable digital storage oscilloscopes (DSO) that may be connected to a personal computer or a laptop via USB-2.0 port. Specialized software must be installed to operate the ADC on the computer.

9)Hall effect current sensors (CS) CSLA1CF of Honeywell Company were used to monitor the current.

3. RESULTS

The mathematical model was studied to establish the effect of the borehole plunger pump electric drive parameters on energy efficiency of its operation, including an open phase CLIM operational mode.

The following equivalent circuit parameters were used for the CLIM and water pump (based on the motor's data sheet provided by the manufacturer): R_1 = 0.5 Ohms, X_1 = 1 Ohm, $X_2^{'}$ = 0.1 Ohm, X_m = 5 Ohms, $R_2^{'}$ = 1 Ohm,V_0 = 3/6 m/s, pole pitch = 0.036 m, the number of pole pairs p = 6, plunger mass – m_p = 3.875 kg; plunger diameter – D_p = 20 mm; pipeline diameter – D_t = 20 mm; the intake pipe diameter – D_{tvsas} = 20 mm; water density – ρ_o = 1000 kg/m^3.

Electric currents produced at start-up, reversing, braking, speed change, load relief and rise exceed nominal values considerably (Figure 3). That is why losses occurring in the motor turn out to be rather significant and affect energy related indices of the electric drive operation as well as lead to its excessive heating. Constant phase switching has a negative impact on the CLIM service life

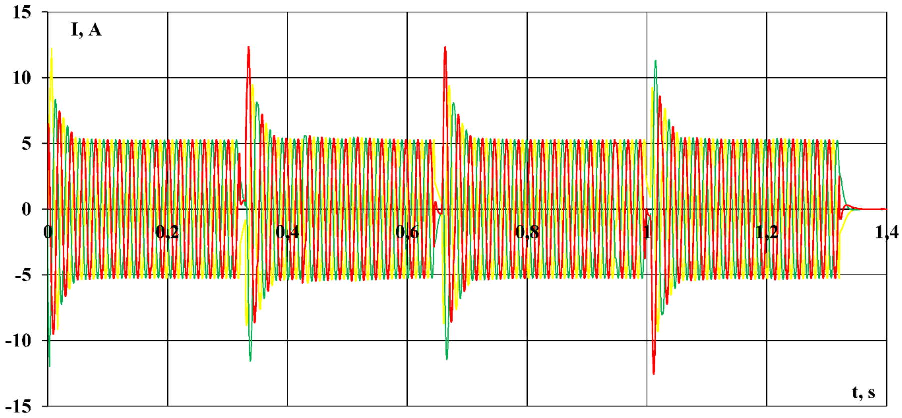

Figure 3: Current in three Phases of the CLIM Operation in Reversing Mode.

The CLIM suffers from the greatest electricity losses in the transient state, as the reverse mode is the main for the motor.

Simulation of the borehole plunger pump operation in the reverse mode (figure 4) showed that the inrush current was 2–2.2· I_{nom}. In one phase switching mode of the CLIM (figure 4), the inrush currents did not exceed 1.62 I_{nom}, so inrush currents dropped in amplitude by minimum 19 %.

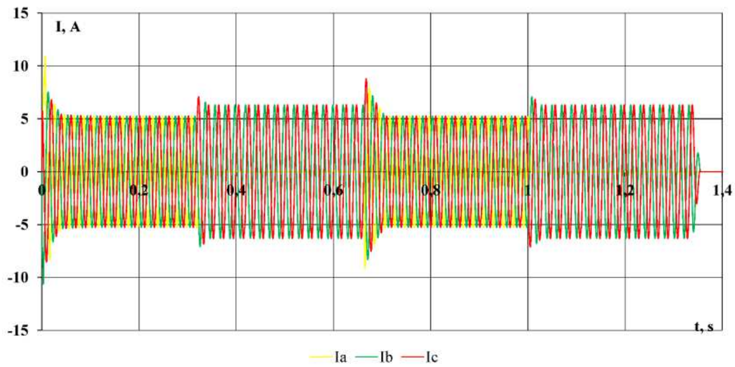

Figure 4: Current In Three Phases In The A-Phase Switching Mode.

The obtained oscillograms of the current consumed by the CLIM inductor (figure 5) demonstrate that the inrush currents drop in amplitude by 19% and in duration by 17%.

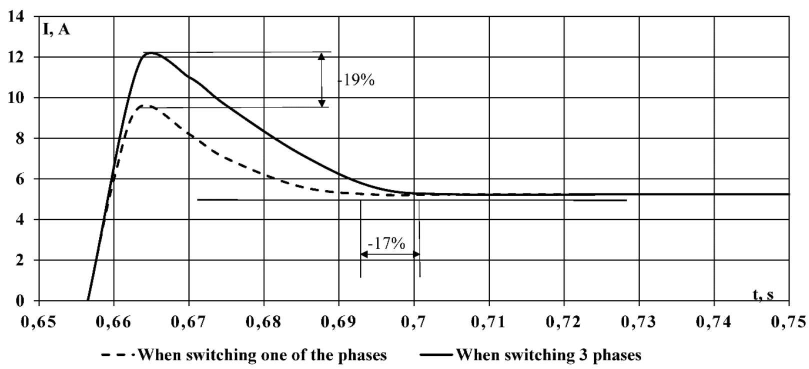

Figure 5: Current in the Three-Phase Switching (Solid Line) and a-Phase Switching (Dashed Line) Modes.

To test the linear electric drive operation at different loads the borehole plunger pump performance was studied under different plunger diameters (figure 6).

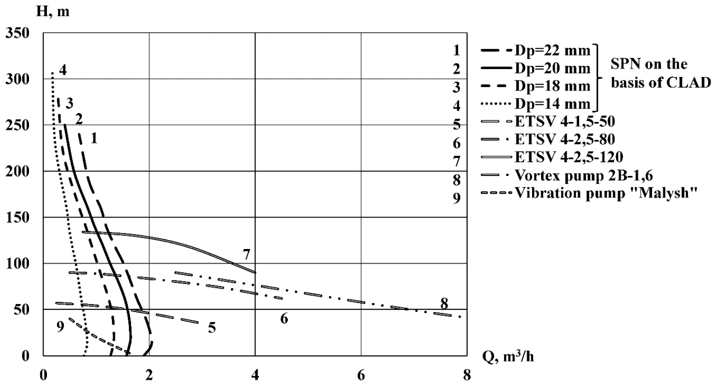

Figure 6: Performance Specifications of the Pump under Study and other type Pumps: H - Discharge Head, Q–Performance.

The graph reads 1–4 borehole plunger pumps with the CLIM based drive, 5 ETSV4-1.5-50, 6 ETSV 4-2.5-80, 7 ETSV 4-2.5-120, 8 regenerative turbine pump 2 V-1.6, 9 vibration pump "Malysh".

The smaller the plunger diameter, the greater the water lifting height. Performance specifications of the most common centrifugal pumps were analysed of ETSV series (ETSV4-1.5-50, ETSV 4-2.5-80 and ETSV 4-2.5-120) featuring discharge head of 50–120 m and performance range of 0.5 ...m^3/h, of regenerative turbine pump 2 V-1.6 and of Vibration pump "Malysh". The analysis shows that the borehole plunger pump with the drive on a CLIM basis enables higher pressures to be achieved while maintaining performance when load is changed. Centrifugal pumps featuring 2 kW capacity and 0.5–2 m^3/h output can ensure the discharge head of up to 100 m, while the tested borehole plunger pump of 1.8 kW ensures discharge head of minimum 200 m at 0.3–1.0 m^3/h output.

Efficiency index showing the rate of the pump effective output to the drive shaft output was used as an economical operation index for pumps under analysis. Figure 7 provides a comparison graph of efficiency to discharge head dependence for different pumps. Efficiency of the borehole plunger pump with the CLIM based drive has higher values over a wide range than efficiency values of centrifugal pumps.

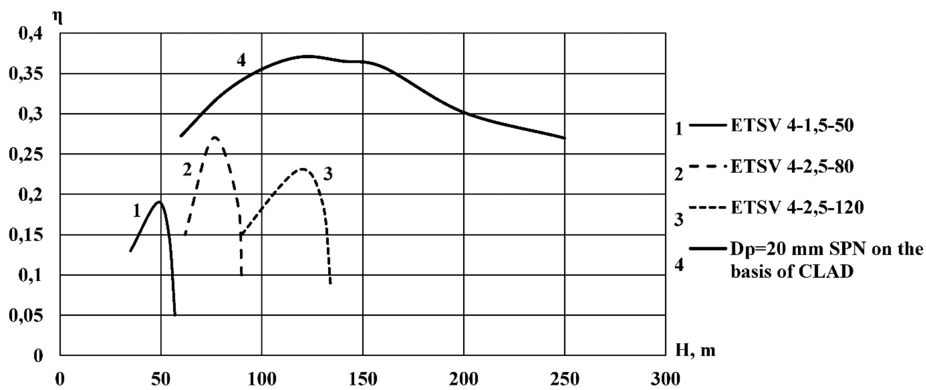

Figure 7: Efficiency-to-Discharge Head Dependence in Different Pumps.

The graph reads: 1 ETSV4-1.5-50, 2 ETSV 4-2.5-80, 3 ETSV 4-2.5-120, 4 borehole plunger pumps with the CLIM based drive.

Figures 8 and 9 show the comparison of the performed experiments and mathematical modelling. Current *I* of the CLIM inductor and the plunger position coordinate X were taken as indices to assess adequacy of the developed mathematical model (figure 9).

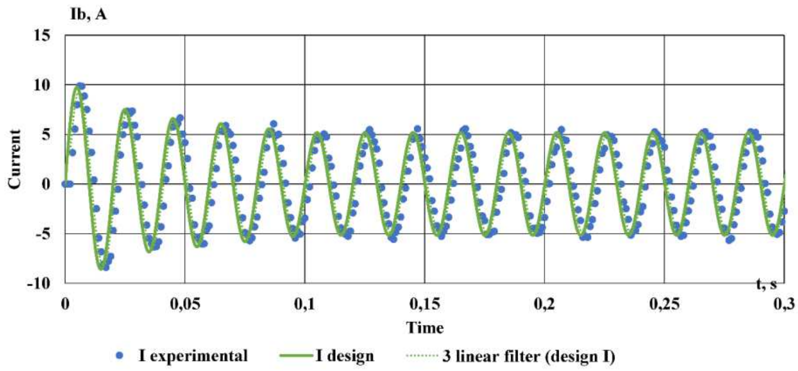

Figure 8: Time Dependence of the Current Consumed Ib by the CLIM Inductor.

The graph reads: large dotted curve–experimental I, solid curve–design I, small dotted curve–3 linear filter (design I).

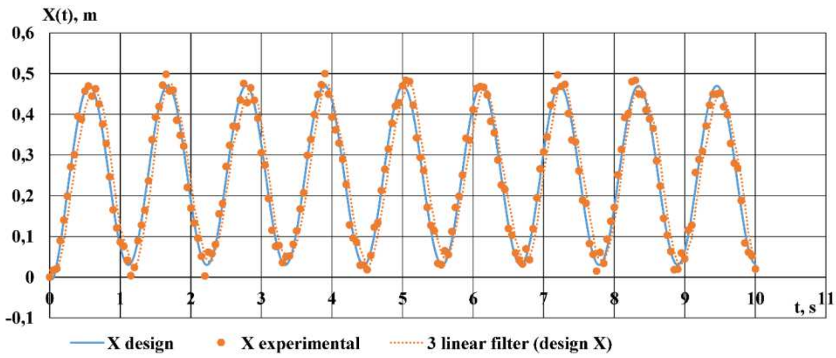

Figure 9: Time Dependence of the Pump Plunger Position X on Time T.

The graph reads: solid curve–design X, large dotted curve–experimental X, small dotted curve–3 linear filter (design X).

The study of the design and experimental dependences of the CLIM inductor current indicates that the difference of inrush current amplitudes does not exceed 0.91 A, which is 12.5% (in the 0–100 ms range), and difference of steady mode current amplitudes does not exceed 0.38 A, i.e., 7.6% (in the 100–300 ms range). Thus, the developed mathematical model of the borehole plunger pump driven by the CLIM may be used in operational analysis and considered as adequately reflecting physical processes.

4. DISCUSSION OF THE RESULTS

- Analysis of the research results and other scientists' studies show that the discussed design of the borehole plunger pump driven by the cylindrical linear induction motor with intermittent phase switching possesses scientific and patent novelty Originality of the engineering solution is protected by the patent of the Russian Federation (Aipov, 2016).

- Studies of the mathematical model demonstrate that the CLIM open phase operation at the reverse stroke of the pump plunger can reduce inrush currents up to 19% in amplitude and up to 17% in duration. Studies have shown that the proposed design and the CLIM open phase operation for driving the borehole plunger pump provide a significant increase in energy efficiency of the pumping equipment. It is established that the maximum efficiency of the borehole plunger pump driven by the CLIM is 0.37. The performance range of 0.8–1.4 m^3/h is the most efficient, as efficiency in this range is minimum 0.33.

- Time dependences of the CLIM inductor phase current and the plunger position are obtained based on the experiments. Experimental results underwent mathematical processing to show that difference in design and experimental data on the plunger position did not exceed 7.7% and on current 12.5%. Thus, the obtained experimental dependences may be considered as accurately corresponding to the theoretic research data and the developed mathematical model adequately reflects physical processes.

5. CONCLUSIONS

- A borehole plunger pump driven by the CLIM was designed featuring a switching circuit to provide an open phase operation mode. The design lowers inrush currents and increases efficiency.
- A mathematical model was developed for the borehole plunger pump driven by the CLIM and equipped with elastic elements of the mechanical energy storage and operating in one-phase intermittent tripping mode at a three-phase power supply. The design was developed to study the drive operation modes and parameters and select the most efficient option.
- An experimental plant and a control system were developed for the borehole plunger pump driven by the CLIM with one-phase switching of the motor at a three-phase power supply.
- Theoretical research and experimental results may contribute considerably to the theory of linear electric motor control and provide sufficient grounding for practical application of the motors in water supply systems employing borehole plunger pumps.

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